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Intro to CO2 Monitoring

Joey Fox · Follow
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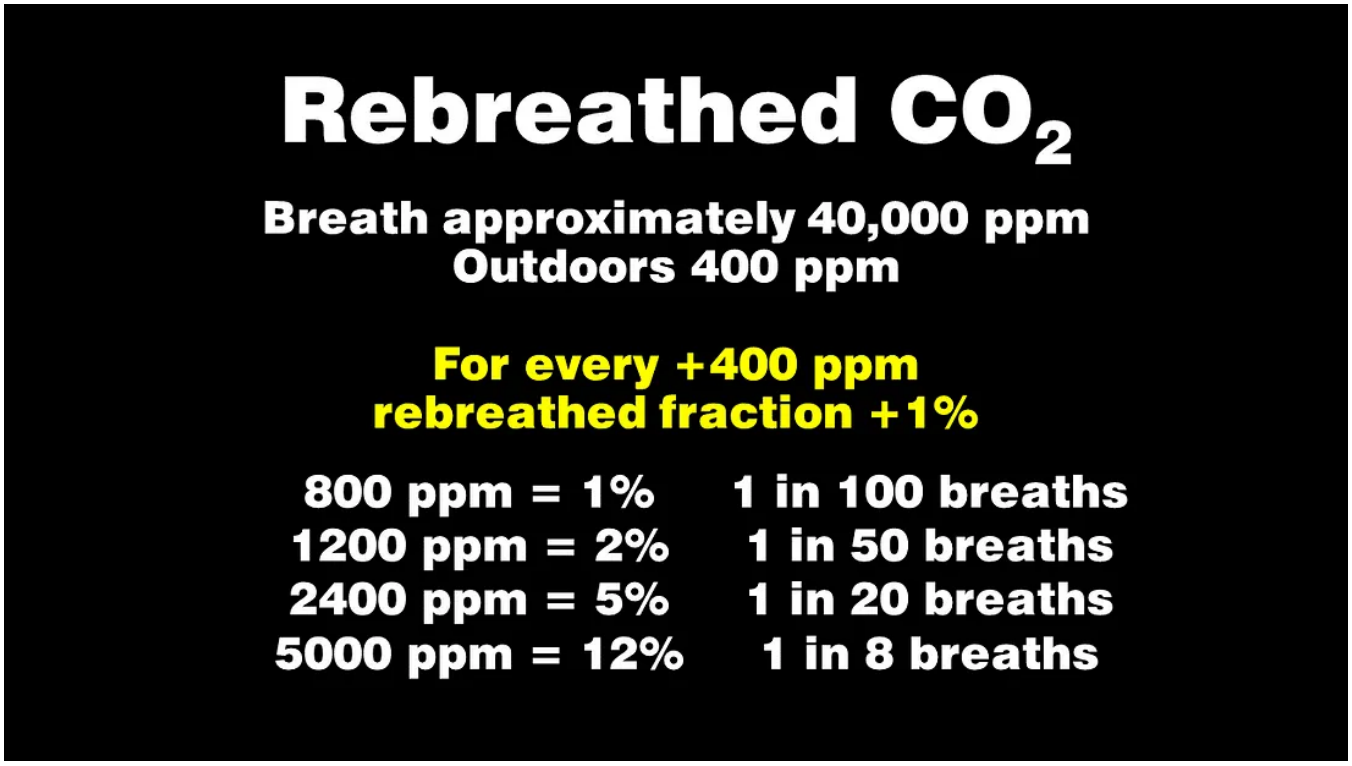
What is CO2?

CO2, or carbon dioxide, is a gas that is found in the air. Measuring CO2 can help assess indoor air quality. The concentration of CO2 outdoors is typically around 420 parts per million (ppm) or 0.042%, but has been climbing over the decades as we burn fossil fuels. When people exhale, the concentration of CO2 in the exhaled air is about 40000 ppm or 4%. If a space is not adequately ventilated, the CO2 levels can increase, indicating that people are rebreathing air that has been previously exhaled (gaseous backwash).


Rebreathed CO_2
Breath approximately 40,000 ppm
Outdoors 400 ppm
For every +400 ppm
rebreathed fraction +1%
800 ppm = 1% 1 in 100 breaths
1200 ppm = 2% 1 in 50 breaths
2400 ppm = 5% 1 in 20 breaths
5000 ppm = 12% 1 in 8 breaths

Credit: David Elfstrom

While CO2 is generally harmless in normal indoor quantities, elevated levels of CO2 can indicate poor indoor air quality, which can negatively affect human health and cognitive performance. Understanding CO2 levels can help us gauge the risk of airborne disease transmission and ensure adequate ventilation to maintain a healthy indoor environment.

Why is CO2 Important?

From all of the different pollutants in the air that can be monitored, it seems like CO2 has the biggest focus. There's a good reason for that.

Harmful pollutants, like fine particulate matter and formaldehyde can be monitored, but they do not really tell you about the ventilation rate. **The important thing about CO2 is that it is the best tool we have to monitor ventilation.**

With few exceptions noted below, CO2 is generally produced by people and removed by ventilation. As explained below, the ventilation rate per person can be directly calculated from the CO2 concentration. There are other methods to monitor ventilation, but CO2 is the only one that actually measures the air that people are breathing.

As ASHRAE notes in their position document: "Indoor CO2 concentrations do not provide an overall indication of IAQ, but they can be a useful tool in IAQ assessments if users understand the limitations in these applications." The reason they do not provide an overall indication of IAQ is because having acceptable ventilation rates is not a guarantee for good air quality. But these ventilation rates are designed to provide acceptable IAQ and CO2 is the best way to confirm them.

It's not perfect, but it is the best tool we have.

CO2 Concentrations

What's Safe?

CO2 can be used in two ways to assess indoor air quality: as a proxy for ventilation or as a direct measurement of CO2 exposure. The American Conference of Governmental Industrial Hygienists sets threshold limit values (TLVs) for CO2 exposure to ensure safe levels of the gas in the air. The TLV for CO2 is 5000 ppm for an 8-hour average and 30000 ppm for short-term exposure. However, it's important to note that safe CO2 levels only relate to the direct exposure to CO2 and do not imply acceptable indoor air quality. Good ventilation levels are typically below 1000 ppm, whereas poorly ventilated areas can range between 1000–3000 ppm. In most circumstances, there is low concern about exceeding CO2 TLVs.

What's Acceptable?

According to ASHRAE's position document on indoor air CO2: "An indoor CO2 concentration below 1000 ppm has long been considered an indicator of acceptable

IAQ".

Similarly, Health Canada recommends an exposure limit of 1000 ppm in residences.

As will be explained below, expected CO2 concentrations can be calculated based on the required ventilation rate. This rate is defined in ASHRAE 62.1 — Ventilation and acceptable indoor air quality. The Ontario Society of Professional Engineers has developed a helpful calculator to estimate the expected CO2 levels in indoor spaces that meet the current ventilation standards: http://ospe-calc.herokuapp.com/.

Here are some typical CO2 levels reported in OSPE's indoor air quality reports for different settings:

- Daycare centers: 850 ppm
- Elementary school classrooms: 900 ppm
- High school classrooms: 1150 ppm
- Offices: 1050 ppm
- Retail stores: 1300 ppm
- Doctor's offices: 1000 ppm
- Dental procedure rooms: 800 ppm

What's Good for IAQ?

The ventilation standard in the building code is only for acceptable indoor air quality and not for good indoor air quality. Recent guidelines have provided ventilation guidance for good IAQ.

ASHRAE's Guideline 42 — Enhanced Indoor Air Quality recommends a ventilation rate 30% above the rates in ASHRAE 62.1 (8.2.1.2). A 30% increase above rates providing 1000 ppm would lead to a CO2 concentration around 800 ppm.

The CDC also states that: "One potential target for the baseline concentrations that is used to represent good ventilation is CO2 readings below 800 parts per million

(ppm)."

800 ppm CO2 appears to be a reasonable target for good IAQ.

What's Good for Airborne Diseases?

CO2 is not directly linked to risk of airborne disease transmission. It is directly linked to ventilation which is one method to mitigate airborne diseases. With poor ventilation, but overall high levels of air cleaning, it is possible to have high CO2, but low risk of airborne disease transmission. Nevertheless, if ventilation is the only mitigation measure used, based on clean airflow rates required in ASHRAE 241, the expected CO2 concentrations would be:

Occupancy Category	Equivalent Clean Airflow (lps/person)	Calculated Equivalent Air Changes per Hour	Calculated Equivalent CO2 (ppm)
Correctional Cell	15	5	710
Correctional Dayroom	20	8	660
Restaurant	30	28	600
Cafeteria	30	40	600
Gym	40	3.7	770
Office	15	1	790
Call Center	15	12	790
Retail	20	4	850
Transportation Waiting	30	40	600
Daycare	20	6.7	620
Elementary School	20	6.7	600
High School	20	9.3	660
Lecture Hall	25	50	620
Manufacturing	25	2.3	770
Sorting, packaging, light assembly	10	0.9	1300
Warehouse	10	0.1	1300
Health Care Exam Room	20	5.3	700
Health Care Group Treatment Area	35	9.3	580
Health Care Patient Room	35	9.3	550
Health Care Resident Room	25	5.3	600
Health Care Waiting Room	45	30	540
Auditorium	25	50	620
Place of Religious Worship	25	40	620
Museum	30	16	700
Convention	30	60	600
Spectator Area	25	50	640
Lobbies	25	50	760
Residential Common Space	25	0.7-5	620
Residential Dwelling Unit	15	0.4-3	710

Required equivalent airflow rates for different occupancy categories. The calculated equivalent CO2 is the steady state value of the CO2 concentration if outdoor air was the only method used to provide clean airflow.

Summary of CO2 Levels

It seems reasonable to conclude for CO2 concentrations:

- Hazardous: 30000 ppm short-term or 5000 ppm 8 hours
- Acceptable: 1000 ppm
- Good: 800 ppm
- Mitigating airborne diseases with no other measures: 600–700 ppm

Calculating CO2 concentrations from ventilation

Warning: this next part uses math, you can skip it.

To understand where these CO2 values originate, it requires some math and knowledge of engineering standards. There are three steps to determining acceptable CO2 levels inline with current standards:

First, calculate the required outdoor airflow rate based on the ventilation rate procedure (VRP) in ASHRAE 62.1, which is the standard for North America. The VRP uses two values from Table 6–1: the flow per person and flow per area. These values are used to determine the total outdoor airflow rate in liters per second (lps). For example, suppose you have a typical classroom with 25 people and 85 square meters. Using Table 6–1, the flow per person is 5 lps and the flow per square meter is 0.6 lps. You can then calculate the outdoor airflow rate as follows:
Outdoor airflow rate = (5 lps/person × 25 people) + (0.6 lps/m^2 × 85 m^2)
Outdoor airflow rate = 176 lps
Outdoor airflow rate per person = 176 lps / 25 people
Outdoor airflow rate per person = 7 lps/person

Second, to determine the CO2 generation rate, you can use this table that provides CO2 generation based on age, gender, and activity level.

Activity	M (met)	Range
Calisthenics—light effort	2.8	
Calisthenics—moderate effort	3.8	
Calisthenics—vigorous effort	8.0	
Child care		2.0 to 3.0
Cleaning, sweeping—moderate effort	3.8	
Custodial work—light	2.3	
Dancing—aerobic, general	7.3	
Dancing—general	7.8	
Health club exercise classes—general	5.0	
Kitchen activity—moderate effort	3.3	
Lying or sitting quietly		1.0 to 1.3
Sitting reading, writing, typing	1.3	
Sitting at sporting event as spectator	1.5	
Sitting tasks, light effort (e.g, office work)	1.5	
Sitting quietly in religious service	1.3	
Sleeping	0.95	
Standing quietly	1.3	
Standing tasks, light effort (e.g, store clerk, filing)	3.0	
Walking, less than 2 mph, level surface, very slow	2.0	
Walking, 2.8 mph to 3.2 mph, level surface, moderate pace	3.5	

TABLE 4 CO_2 generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity (based on mean body mass in each age group)

			CO_2 generation rate (L/s)						
			Level of physical activity (met)						
Age (y)	Mean body mass (kg)	BMR (MJ/day)	1.0	1.2	1.4	1.6	2.0	3.0	4.0
Males									
<1	8.0	1.86	0.0009	0.0011	0.0013	0.0014	0.0018	0.0027	0.0036
1 to <3	12.8	3.05	0.0015	0.0018	0.0021	0.0024	0.0030	0.0044	0.0059
3 to <6	18.8	3.90	0.0019	0.0023	0.0026	0.0030	0.0038	0.0057	0.0075
6 to < 11	31.9	5.14	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0100
11 to <16	57.6	7.02	0.0034	0.0041	0.0048	0.0054	0.0068	0.0102	0.0136
16 to <21	77.3	7.77	0.0037	0.0045	0.0053	0.0060	0.0075	0.0113	0.0150
21 to < 30	84.9	8.24	0.0039	0.0048	0.0056	0.0064	0.0080	0.0120	0.0160
30 to <40	87.0	7.83	0.0037	0.0046	0.0053	0.0061	0.0076	0.0114	0.0152
40 to <50	90.5	8.00	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0155
50 to <60	89.5	7.95	0.0038	0.0046	0.0054	0.0062	0.0077	0.0116	0.0154
60 to <70	89.5	6.84	0.0033	0.0040	0.0046	0.0053	0.0066	0.0099	0.0133
70 to <80	83.9	6.57	0.0031	0.0038	0.0045	0.0051	0.0064	0.0095	0.0127
≥80	76.1	6.19	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
Females									
<1	7.7	1.75	0.0008	0.0010	0.0012	0.0014	0.0017	0.0025	0.0034
1 to <3	12.3	2.88	0.0014	0.0017	0.0020	0.0022	0.0028	0.0042	0.0056
3 to <6	18.3	3.59	0.0017	0.0021	0.0024	0.0028	0.0035	0.0052	0.0070
6 to < 11	31.7	4.73	0.0023	0.0027	0.0032	0.0037	0.0046	0.0069	0.0092
11 to < 16	55.9	6.03	0.0029	0.0035	0.0041	0.0047	0.0058	0.0088	0.0117
16 to <21	65.9	6.12	0.0029	0.0036	0.0042	0.0047	0.0059	0.0089	0.0119
21 to < 30	71.9	6.49	0.0031	0.0038	0.0044	0.0050	0.0063	0.0094	0.0126
30 to < 40	74.8	6.08	0.0029	0.0035	0.0041	0.0047	0.0059	0.0088	0.0118
40 to <50	77.1	6.16	0.0029	0.0036	0.0042	0.0048	0.0060	0.0090	0.0119
50 to <60	77.5	6.17	0.0030	0.0036	0.0042	0.0048	0.0060	0.0090	0.0120
60 to <70	76.8	5.67	0.0027	0.0033	0.0038	0.0044	0.0055	0.0082	0.0110
70 to <80	70.8	5.45	0.0026	0.0032	0.0037	0.0042	0.0053	0.0079	0.0106
≥80	64.1	5.19	0.0025	0.0030	0.0035	0.0040	0.0050	0.0075	0.0101

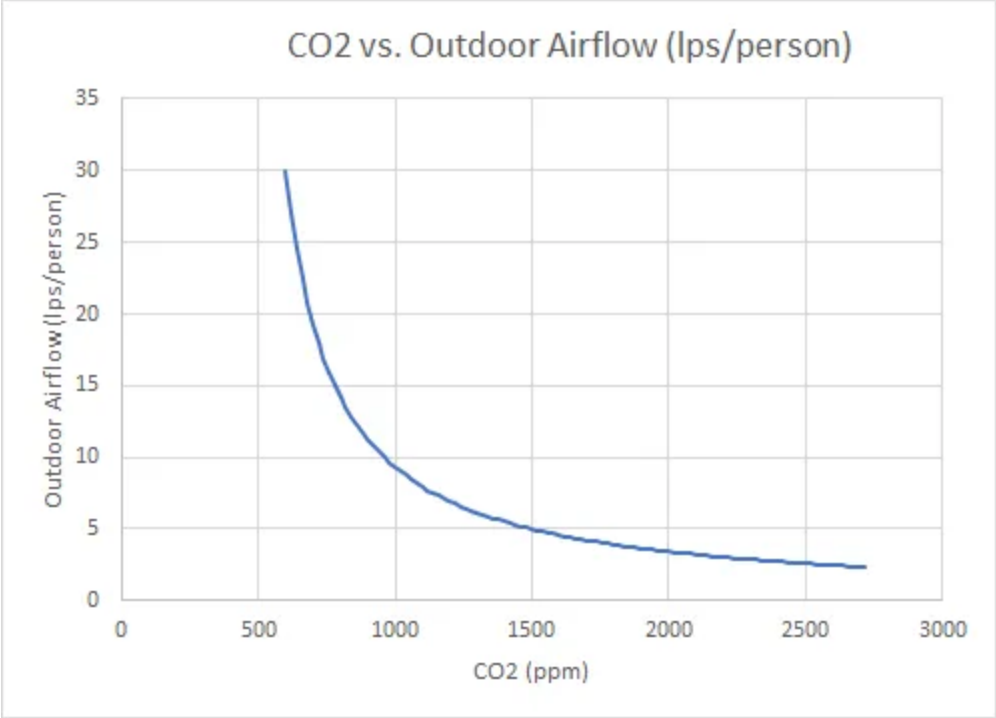
For example, if you have a 15-year-old male student who is sitting and writing in a classroom, his metabolic rate is 1.3 according to the first table. Using the second table, you can determine the corresponding CO2 generation rate, which is between 0.0041 and 0.0048 lps. This equates to around 0.0045 l/s per person.

Finally, once you have the outdoor airflow rate and CO2 generation rate, you can use the following formula to calculate the steady-state indoor CO2 concentration:
Indoor CO2 = Outdoor CO2 + (generation rate × 1 000 000) / outdoor airflow rate

For example, using the values from the previous steps:
Indoor CO2 = 420 ppm + (0.0045 l/s per person × 1,000,000) / 7 lps/person
Indoor CO2 = 1062 ppm

This calculation provides an estimate of the steady-state indoor CO2 concentration. You can use this information to determine whether the indoor CO2 level meets acceptable levels for the space in question.

This is a plot of expected CO2 levels vs outdoor airflow rate per person.



The formula can also be reversed to diagnose outdoor airflow rate based on CO2 levels. For a classroom, if the steady state CO2 concentration is 1200 ppm, then the outdoor airflow rate is:
Outdoor airflow rate =(generation x 1 000 000)/(Indoor CO2 — Outdoor CO2)

= (0.0045 x 1000000)/(1200–420)=5.8 lps/person

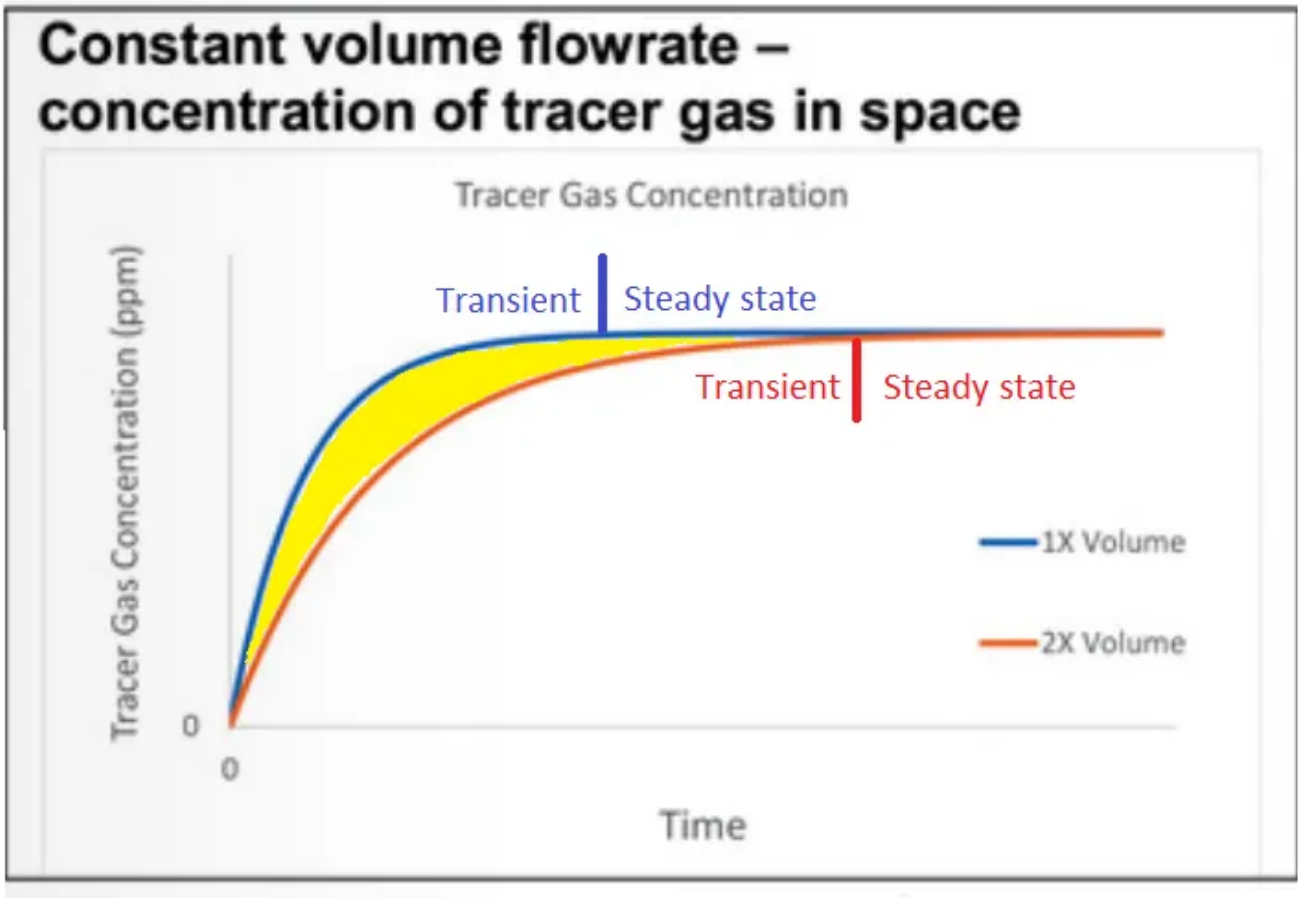
This is lower than the minimum requirement in ASHRAE 62.1 and almost half of the 10 lps/person recommended by the WHO.

Transient time and temporary readings

Buildings are not completely airtight, and air can leak in and out through the building envelope, a process known as infiltration and exfiltration. If a room has been unoccupied for some time, the previously exhaled air by occupants would have leaked out of the building, and the CO2 levels in the room should be similar to the outdoor air CO2 levels of around 420 ppm.

As occupants spend more time in the space, the CO2 levels will begin to rise, which is referred to as the transient state. Once the rate at which CO2 is generated matches

the rate at which it is removed, it reaches a steady state. In larger rooms, the air volume is greater, and it takes a longer time to reach the steady state, as illustrated in this plot:



A graph showing the transient state and steady state in two rooms. The smaller room (blue line) reaches steady state much quicker than the larger room (red line). The steady state concentration is independent of room size. The yellow area is the reduced concentration of the pollutant people would be exposed to in a larger room. http://portfolio.cpl.co.uk/CIBSE/202106/42/

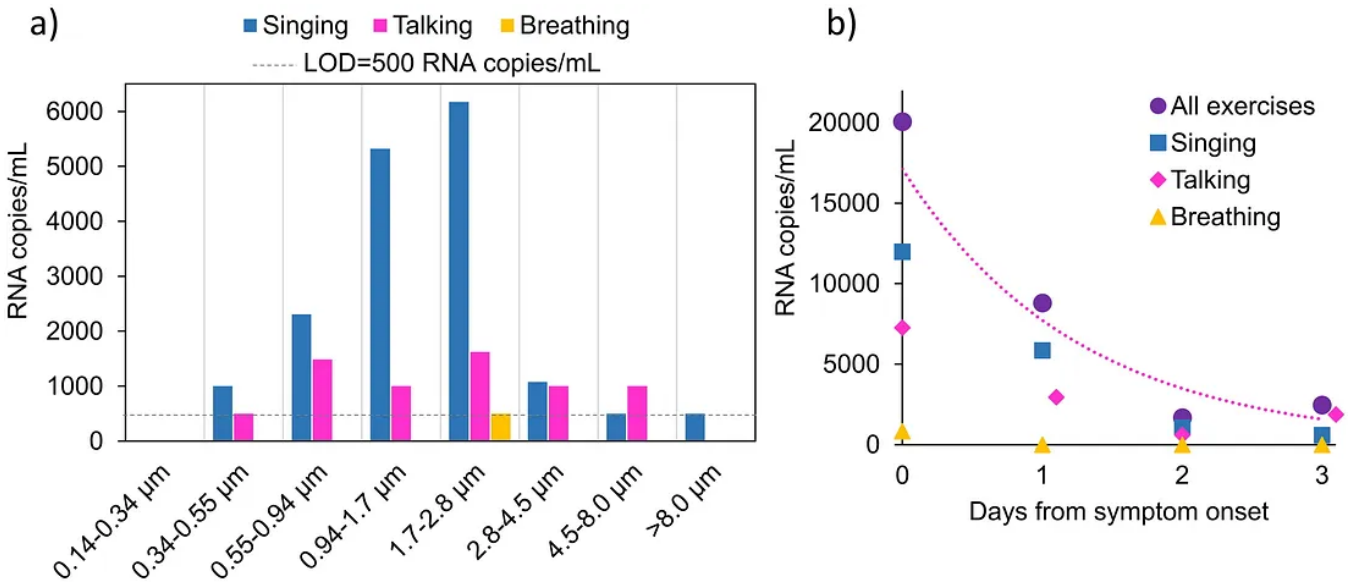
However, other factors can temporarily affect the CO2 levels, such as a person breathing near the CO2 sensor, which can show a high CO2 concentration that does not represent the actual air quality of the space. Additionally, when people enter or leave the room, their metabolic rate increases, causing a temporary increase in CO2 levels.

Assessing Risk for Airborne Disease Transmission

To assess the risk of airborne transmission of any pollutant, including infectious aerosols, it's important to consider the concentration of that pollutant in the air.

This concentration is affected by both the rate at which it's generated and the rate at which it's removed. When it comes to infectious aerosols and CO2, comparing their generation and removal can help us understand the relationship between them.

Infectious aerosols are generated by infectious people, and the rate of generation depends on the activity level.



Figures showing aerosol generation based on different activities. Exercising (purple), singing (blue), and talking (magenta) have much higher rates than breathing alone (yellow). https://www.tandfonline.com/doi/full/10.1080/23744235.2022.2140822

CO2, on the other hand, is generated by all people and combustion reactions, and is removed through ventilation or sorbent-based removal systems. Infectious aerosols can be removed by various means, such as ventilation, filtration, UV light, natural decay, or deposition (landing on surfaces).

Here's how infectious aerosols and CO2 are related:

- CO2 generation increases with more people, and so does the risk of having an infectious person present.
- CO2 and infectious aerosol generation both increase with higher activity level.
- CO2 and infectious aerosol concentration both increase with poor ventilation.

However, there are also ways in which CO2 is not related to the risk of airborne

disease transmission:

- When people are just exhaling and not talking or exercising, infectious aerosol generation can be very low, but CO2 generation can still be at a normal level.
- Filtration and UV light can reduce the concentration of infectious aerosols in the air, but they do not affect CO2 levels.
- If CO2 is generated from combustion reactions or sublimating dry ice, the CO2 concentration will increase without an increase in infectious aerosol concentration.
- CO2 can be removed from the air through sorbent-based removal systems, but these systems are not designed to capture particulate matter like infectious aerosols.
- Infectious aerosols are only generated by infectious people. If there are no infectious people present, there is no risk of transmission, even if CO2 levels are high.
- In larger rooms, infectious aerosols have a larger volume of air to disperse in, which means they have a longer average travel distance before reaching a susceptible person. This increased travel distance increases the time between emission and inhalation, which allows more time for infectious aerosols to decay or settle out of the air before being inhaled. Therefore, the risk of infection from airborne transmission is generally lower in larger rooms compared to smaller rooms with the same number of people. CO2 does not decay or settle.

ASHRAE's position is that "all else being equal, higher CO2 concentrations correspond to lower outdoor air ventilation rates and the potential for an increased risk of airborne transmission" while acknowledging many of the limitations stated here.

Often, ventilation is the only indoor air quality method employed in many spaces, so CO2 concentration can be a very helpful tool for individuals to assess risk. However,

given the limitations, the most accurate use of CO2 monitoring for operating buildings is to ensure that ventilation is functioning properly, as ventilation is the main method used to ensure adequate air quality.

Risk Assessment Between Two Cases

When comparing two situations and assessing risk, it's important to use the correct metric. The metric that matters for airborne virus transmission is infectious aerosol generation versus total airflow.

Let's consider two cases: the first case involves two people, one of whom is infectious, with 15 lps of outdoor air per person and 700 ppm CO2. The second case involves ten people, one of whom is infectious, with 5 lps of outdoor air per person and 1250 ppm CO2.

In the first case, the total airflow is 30 lps, while in the second case, the total airflow is 50 lps. However, since the infectious aerosol generation is the same in both cases, the second case with more people and higher CO2 would still be considered lower risk because the total airflow per infectious person is higher.

It's important to note that this does not mean 1250 ppm is a low-risk level, but rather that 700 ppm is much higher risk than would be expected in this case. As a general rule of thumb, low CO2 levels should not be used as an indicator of low risk if there are fewer than ten people in a confined space. As the number of people increases, the risk increases due to the higher likelihood of encountering an infectious individual.

Risk Assessment with Low Occupancy

The previous case existed because CO2 is related to the outdoor airflow rate per person, while protection from airborne diseases is related to the total clean airflow rate. Therefore, as the occupancy drops, CO2 levels are expected to drop too, but there could be an overall low airflow rate. Therefore, lower CO2 concentrations would be required when there are fewer people if one person is infectious.

As discussed in this post, if ventilation is the only tool, CO2 concentrations indicating low risk of airborne transmission, would be:

6 people: 620 ppm

5 people: 590 ppm
4 people: 550 ppm
3 people: 520 ppm
2 people: 490 ppm

What alternatives are there to CO2 monitoring?

Individuals can use CO2 as part of an airborne disease risk assessment, but from a building operation perspective, the primary utility of CO2 is to verify ventilation rates. There are other methods available, each with their own advantages and disadvantages. These methods include:

- Checking airflow from the HVAC system
- Using a pollutant tracers decay
- Doing a fog study
- Professional commissioning and airflow measurements
- Using a building automation system

These methods, along with CO2 are discussed in more detail in this post:

6 Ways to Check Mechanical Ventilation

Creating a safe and healthy indoor environment is essential for our wellbeing and ventilation systems are the primary...

itsairborne.com

How to use a CO2 monitor

To use a CO2 monitor, it's recommended to use the most accurate sensor called non dispersive infrared (NDIR). When placing the CO2 monitor, avoid placing it near people, windows, doors or air vents. Instead, it should be placed at a height of 1.5 m on a wall in a location that is representative of the air being inhaled by the occupants. Avoid placing it inside HVAC ducts as it may not represent the same pollutant concentration as the space.

CO2 measurements can be used to quickly gauge how much air is being rebreathed. However, in places where people must be present like schools, offices, healthcare facilities or congregate living settings, steady state CO2 levels can be used to determine if the ventilation is meeting current standards.

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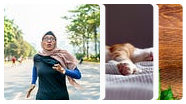

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